Deep Space One Spacecraft System Engineering Techniques and the Application of Heuristic Reasoning

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Abstract. The Deep Space One Project is part of the National Aeronautics and Space Administration's (NASA's) New Millennium Program. The team is chartered with the design, development, and in-flight validation of new technologies. The knowledge gained in flight will be instrumental in the success of future projects as they strive to build "faster, better, cheaper" spacecraft for NASA, the nation, and the world. There are a total of twelve new technologies planned to fly as part of the first deep space mission, many of which were either selected by the program and/or project manager independently or some that were coupled unconditionally with one another. These technologies include the miniature imaging camera and spectrometer, autonomous on-board optical navigation, and the small deep space transponder. However, the most striking of these are arguably the ion propulsion system and advanced solar concentrator array, the combination of which will result in a ten fold or order of magnitude increase in impulse (ratio of force over the propellant mass) over a conventional chemical system. At the time of this writing, the Deep Space One Project is nearing completion of the thirty-three month development life cycle and is being mechanically and electrically integrated and tested at the Jet Propulsion Laboratory in Pasadena, California. This paper discusses the system engineering techniques used to date, especially the application of heuristic reasoning, in the design, development, and test of the Deep Space One spacecraft.

HEURISTIC REASONING

(Rechtin 1991) condenses three entirely different methodologies used in system design into the normative, rational, and argumentative approaches. The normative method is of greatest value when a single decision maker is knowledgeable and proficient in the system being designed. The rational method is based on proven processes or procedures, much like in mathematics where closed-form solutions can be obtained. Finally, the argumentative method is one where one's assertions are accepted and respected. These three methodologies are valid for what could be argued as simple or straightforward systems, but what about complex and/or never before created systems? This is where heuristic reasoning is of greatest value. Heuristics are essentially insights and lessons learned gained from professional training and experience.

In the area of robotic space exploration, the Jet Propulsion Laboratory (JPL) is challenged with research, development, and implementation of new, never-before used technologies to gain scientific knowledge. Many times there are no "cookbooks" for spacecraft development. Since JPL is managed by an educational institution, the California Institute of Technology, individuals who have earned advanced degrees in engineering, science, and mathematics are looked upon with high regard. The more formal education one has, the more interesting and challenging technical and managerial roles become accessible. However, academics is not the only factor when considering candidates for positions of greater responsibility. Related professional experience and the ability to get the job done are also important. Individuals earn a great deal of respect not only by having successfully achieved the requirements and goals of previous projects, but also by facing and overcoming adversity. JPL takes advantage of this wealth of knowledge by selecting review board members that possess insights into the spacecraft development process gained only through both positive and negative personal experiences. In addition, a lab-wide lessons learned document is available over the world wide web, so that project and program personnel can learn from each other and not repeat past mistakes. This collective knowledge then forms the basis for heuristic reasoning in the design of current and future spacecraft for robotic

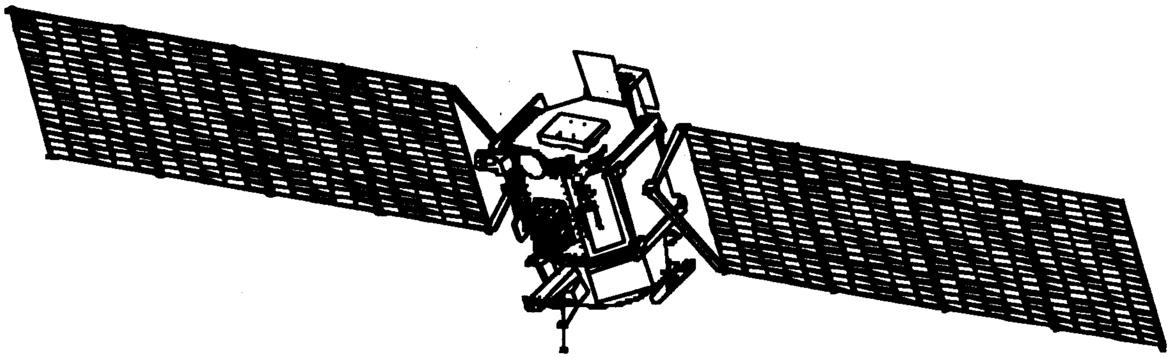

Figure 1 Deep Space One Spacecraft with Solar Arrays Deployed

space exploration. This paper describes one of JPL's newest complex systems, the design methodologies used, and an assessment of which heuristics were found to be most true.

DEEP SPACE ONE PROJECT

NASA's New Millennium Program is comprised of a series of advanced technology in-flight validation missions. (Ridenoure 1996) states that a series of deep-space missions are being defined and implemented by JPL concurrently with a series of Earth-orbiting missions defined and implemented jointly by JPL and the Goddard Space Flight Center. Deep Space One (DS1) is the first deep-space mission. (Rayman, Lehman 1997) state that like all New Millennium Program missions, the main objective of DS1 is to space-validate a suite of advanced technologies - the payload for these missions. The validation of these technologies gives promise to enabling 21st century space science missions with low development life cycle and mission operations costs. There are twelve such technologies for DS1 which include the miniature imaging camera and spectrometer, autonomous on-board optical navigation, and the small deep space transponder. However, the most striking of these are arguably the ion propulsion system and advanced solar concentrator array, the combination of which will result in a ten fold or order of magnitude increase in impulse (ratio of force over the propellant mass) over a conventional chemical system. An illustration of the spacecraft in the nominal cruise configuration is shown in Figure 1.

A mission profile or spacecraft trajectory was chosen which serves as an appropriate test track for the selected complement of advanced technologies. The baseline mission profile includes a near-Earth asteroid encounter, a Mars planetary flyby, and a comet encounter. Development of the DS1 mission differs significantly from more recent JPL missions in that it is being implemented under a technology-driven paradigm as opposed to the typical science-driven one. Science data collection and transmission is planned to take place during the course of the mission as part of the overall technology validation process, however, this objective is considered and understood to be secondary in nature.

At the time of this writing, the Deep Space One Project is thirty-one months through the thirty-three month development life cycle, and spacecraft mechanical, electrical, and software integration and test at the Jet Propulsion Laboratory in Pasadena, California, is nearing completion. Outstanding activities include integration of most final deliveries with the exceptions of the solar arrays, the plasma experiment for planetary exploration, and some thermal blanketing. These items will be integrated following transportation of the spacecraft to the Kennedy Space Center, which is scheduled for 08 May 1998. The window for launch at Cape Canaveral Airforce Station, Florida opens 21 July 1998 and closes on 07 August 1998. The nominal mission for DS1 is scheduled for twenty-four months. A contingency window allows for a launch extension through 14 August 1998, but with a shortened test track.

DS1 DESIGN METHODOLOGIES

Much of the design methodology used in the development of the DS1 spacecraft and mission was documented as part of the Project [Implementation] Plan. Although providing a high-level structure from which to work, there's far more from an approach and process perspective that is not documented in this plan. This paper takes selected excerpts from the Project Plan and also identifies undocumented, but still interesting design methods to develop a notable compendium from which assessments can be formulated.

SPACECRAFT SYSTEM ARCHITECTURE

The DS1 spacecraft design is a centralized one, as opposed to being distributed in nature. The avionics 'subsystem' provides the core capabilities necessary to operate the spacecraft in flight. At the heart is the IEM (Integrated Electronics Module) which contains a VMEbus (Versa Module Eurocard data bus) and thirteen integrated avionics boards. The slot 1 system controller for the IEM/VMEbus, and for that matter the entire spacecraft, is the Millennium Flight Computer, a radiation-hardened RISC (Reduce Instruction Set Computer) 6000 processor of Lockheed Martin heritage. The processor operates at 20 Mhz (Megahertz) and possesses 128 MB (Megabyte) of DRAM (Direct Random Access Memory). It is a proven design, having flown just recently as part of the Mars Pathfinder spacecraft as the lander computer. Overall, the spacecraft platform follows the philosophy of being flight qualified on a previous spacecraft. It is the payload, the new technologies, which have never been flown before. One of the avionics boards located in the IEM is the BTF (Bus Transfer Function), which provides bus controller functions for the MIL-STD-1553B data bus, another important component of the avionics. Sensors and actuators, both proven platform components and new payload components are then interfaced to this data bus as remote terminals. The use of a standard VMEbus and standard MIL-STD-1553B data bus is consistent with (Rechtin's 1991) heuristic:

In partitioning, choose the elements so that they are as independent as possible, that is, elements with low external complexity and high internal complexity.

Communications over either bus is accomplished through the use of standard protocols making external component interfaces as simple as possible. Most of the avionics electronics boards have been designed with these types of standard interfaces. The few components that are highly complex such as the miniature camera and spectrometer and multifunctional structure are first interfaced to a custom electronics board that provides the translation or conversion from this highly complex external interface to a standard VMEbus one.

The spacecraft system block diagram essential shows a functional decomposition of capabilities. An alternative approach would have been to use an object-oriented paradigm that is now widely used in software development, including the DS1 flight software. This alternative approach has not been known to be used at JPL for any type of system other than software. Although it would have been an interesting experiment, the DS1 team has left this challenge for a future project. The functional decomposition approach is appropriate and adequate for DS1, and the resulting system architecture could not have been created without much additional system architecture and engineering work. The overall system is comprised of subsystems that support the overall infrastructure. Traditionally, subsystem boundaries at JPL divided command and data handling from attitude and articulation control functions. On DS1, similar to what was recently done on Mars Pathfinder, the two were combined together. Individuals supporting the overall development of the system understood that,

choosing the appropriate aggregation of functions is critical in the design of systems

another heuristic identified by (Rechtin 1991). It was believed that there was an architecture and an associated organization that would work well for DS1.

Division of Responsibilities. In contrast to the project's alignment or consistency with the partitioning of a spacecraft system in which local activity is high speed and global activity is slow to change, the organization structure or personnel assignments were and are still such that a considerable amount of time is spent interfacing. (Rechtin's 1991) heuristic states the following,

organize personnel tasks to minimize the time individuals spend interfacing.

Although there have been tremendous benefits, the selection of an industry partner located hundreds of miles from JPL has been a communications challenge. With the advent of electronic mail and videoconferencing to augment regular correspondence, telephone conversations, and frequent site visits for 'face-to-face' discussions it would not be unreasonable to believe that regular, effective, and satisfactory communications could be achieved. Unfortunately, there have been numerous instances where critical technical information was not given in a timely manner or not conveyed at all. This could be considered leaving the DS1 project team vulnerable to (Rechtin's 1991) heuristic,

unless everyone who needs to know does know, somebody, somewhere, will foul up.

One of the biggest challenges is in the area of electrical hardware and flight software interfaces. Electrical hardware design, fabrication, and assembly and device driver code are the responsibility of the DS1 industry partner, SAI (Spectrum Astro, Inc.) and flight software system engineering and development, including hardware managers, is the responsibility of JPL. This division of responsibilities is merely an understanding that,

being good at one thing does not automatically mean being good at something else.

a heuristic identified by (Rechtin 1991). Unfortunately, not being in close proximity has had it's drawbacks. Even though previous project examples could be cited where synergy was gained by allowing hardware and software engineers to work side-by-side, the charter or requirement to work with an off-site industry partner makes this difficult to achieve on DS1. However, this dilemma is symptomatic of a larger and more general problem of not be able to collocate most of the project's team members - or not to do so soon enough. Although much of the team is now collocated, a good portion is still isolated in another area (e.g. flight software development). Many would agree that in this type of situation it is difficult to remain focused given non-DS1 related distractions and a lack of constant feedback. There's great benefit in working in an environment immersed only with DS1 spacecraft development activities, especially on an aggressive schedule.

Although upper management recognized the need to support collocation, the institution must understand that if projects are to be completed on shorter and more aggressive schedules, then it must react more quickly to individual needs. However, the institution as a whole is moving in the right direction.

Requirements Definition. The DS1 Team, being fully aware that the project is cost and schedule constrained, understood the need to accept only those flow-down of high-level requirements that would assist in meeting the defined set of success criteria. This was stated time and time again during the initial phase of development and is consistent with (Rechtin's 1991) heuristic,

extreme requirements should remain under challenge throughout system design, implementation, and operation.

Without implementation of this basic philosophy, it would be difficult for the project team to complete the task of building, testing, and operating the spacecraft within the given constraints. Unfortunately, it seems that as the project has moved from design to development and eventually into test, this philosophy is no longer in the forefront of everyone's mind. It sometimes becomes lost due to the high level of activity and the number of challenges that must be dealt with in real-time. Thinking short-term and handling immediate crisis then becomes the "breeding ground for creeping requirements". It is at this time that those with vision, developed over time through training and experience, remind the younger and energetic set to be aware of the overall picture and reduce complexity as much as possible. This is especially true with DS1. There are enough challenges associated with developing and flight validating new technologies. Why compound the situation by adding artificial or self-induced complexity and jeopardizing the project's cost and schedule position?

System Engineering. The system engineering function compliments the system architect's role by bringing form to function. The system engineering team also present at project inception is scheduled to continue with it's roles and responsibilities through completion of the development life cycle, launch, and finally mission operations and data analysis. The exact staffing level is dependent upon the phase of the project and the specific needs of the subsystem teams.

System engineers worked with the System Architect in the interpretation of the high-level program and project requirements, level 1 and 2, respectively, and translating and developing from these System, or level 3, requirements which are formally documented. From these, the element managers or cognizant engineers for each of the subsystems develop their own set of level 4 requirements from which eventually product functional specifications for subsystem components can be derived. The overall set of requirements are also associated with another document, the verification test matrix, which is discussed later in the Verification and Validation section. It is addressed here, because of the importance of "testability" in the design of a system. There have been many lessons learned identified by integration and test personnel on past programs and projects. Numerous interoffice memorandums have been written reminding system engineers and designers to remember to factor in this feature, since,

to be tested, a system must be designed to be tested

a heuristic identified by (Rechtin 1991). There have been instances in the past where requirements were generated, but they could not be verified or validated due to a lack of visibility and had to be inferred as correctly implemented. Quite a risk, especially on current projects which have very little in terms of redundant functions or graceful degradation designed in.

In keeping with the heuristic identified by (Rechtin 1991),

the greatest leverage in system architecting is at the interfaces,

mechanical and electrical interface control documents are also generated. The importance and criticality of interface definitions cannot be overstressed. If defined and implemented correctly, mechanical fit checks and electrical interface compatibility verification can be completed in short order. If not, a considerable amount of time and effort could be spent to overcome interface challenges. A case in point, a mechanical interface document for the integrated electronics module was created based on final physical drawings of avionics electronic boards, including the flight computer. When the time came to replace the commercial processor that had been used in the flight integrated electronics module to date with one of the flight computers, it was found not to fit. An investigation concluded that the mechanical interface control document had one incorrect physical dimension specified for the flight computer. The responsible individual made an incorrect assumption about the compliance to standard VMEbus electronic board dimensions/physical envelope and the integrated electronics module was machined to incorrect specifications. Is this an example of (Rechtin's 1991), heuristic below?

The greatest dangers are also at the interfaces.

It's believed so, given that the flight spare integrated electronics module had to be machined correctly, the flight one replaced with the flight spare and eventually machined correctly itself. Given an aggressive development schedule, this work could only be accommodated during non-standard work hours with engineers and technicians working one weekend.

Finally, although not a standalone compendium or single document, the flight and ground FMECAs (Failure Modes, Effects, and Criticality Analysis') provide information on the probable failures of certain components and what potential adverse effects could be propagated across mechanical, but mostly electrical interfaces. (Rechtin's 1991) heuristic,

be sure to ask the question, "What is the worst thing that other elements could do to you across the interface?,

is a guideline that is well known and understood by many system engineers to be of significant importance. Designers of electrical ground support equipment have ensured that proper opto-isolation is provided in the event of fault propagation, and will help to minimize any damage or degradation of the flight spacecraft. This is equally important for fault isolation of flight spacecraft interfaces. It could be mission catastrophic and embarrassing if a "non-essential" component or electronics board were to bring down the entire spacecraft system, because of improperly designed interfaces. Finally,

testing, without understanding the multiple failure mechanisms to which a system is susceptible, can be both deceptive and harmful,

a heuristic described by (Rechtin 1991). Integration and test personnel will be engrossed with test procedure generation, test execution, and test reporting. It is the responsibility of system engineering to understand the failure modes and to develop test cases from which the integration and test personnel can develop valid detailed test procedures.

In examining the 'documents' mentioned earlier, this list along with the command and telemetry dictionaries, critical to the operations of the spacecraft, are probably the most referred to written sources of information. Therefore,

amid awash of paper, a small number of documents become critical pivots around which every project's management revolves,

(Rechtin's 1991) heuristic applies to the DS1 project as well. The DS1 electronic library, accessible through a web browser, registers the most requests to the documents or references identified previously. Although no exact statistics are known to be recorded, it is a safe bet that at least one-half of all documents requested from the library is for one that has been mentioned or described in this section.

Design Concurrence. The typical spacecraft development life cycle at JPL includes the preliminary design review and the critical design review near the very start of project inception. Normally, the review boards for these meetings would consist of current and former JPL managers and engineers and also outside consultants with similar experience. The review boards are chartered with reviewing presented material and assigning action items as appropriate. In an effort to "empower" the current JPL project teams, the design reviews have now been termed differently. For DS1, the preliminary design review became the preliminary design concurrence and the critical design review became the detailed design concurrence. Review board membership was now open to peers rather than strictly senior level management and engineering personnel, and more importantly, action items became advisories. This allowed the assigned individuals to use their discretion and accept, decline, or modify review board recommendations. In the past, a review board action items required mandatory responses.

For DS1, the preliminary design concurrence was scheduled to take place soon after official project start. Fortunately the team, which included the system architect at the time, was able to do a great deal of design work during the pre-project stage. This allowed for essentially a "head start", without which would have made the task of preparing for a preliminary design concurrence a difficult, if not impossible, task. By reviewing the architectural design this early in the process it allowed for an independent assessment of whether or not the project was starting out on the correct path. This is consistent with (Rechtin's 1991) heuristic,

once the architecture begins to take shape, the sooner contextual constraints and sanity checks are made on assumptions and requirements, the better.

A few months passed before the detailed design concurrence to allow the project team to examine the review board's recommendations and make necessary changes. This too is consistent with another heuristic identified by (Rechtin 1991),

You cannot avoid re-design. It's a natural part of design.

Once the 'final' system architecture has been presented at the detailed design concurrence, any 'updates' would be incorporated through the use of engineering change requests to document alterations to the baseline system design. A change board consisting of the spacecraft development manager, system engineering staff, affected subsystem personnel, and the spacecraft integration and test manager would convene and pass judgment on these requests based on the rationale for and impacts of the potential changes. Recall that the system architect, who would be quite valuable as a member of this change board, was no longer available to fill this role.

At some point in time,

Concept formulation is complete when the builder thinks the system can be built to the client's satisfaction.

This is a heuristic identified by (Rechtin 1991). This occurred in the April 1997 timeframe, after the major tiger team recommendations were made. Although significant challenges remained, the overall system design and the project team that has been formed increase the odds of success.

Verification and Validation. The task of integrating and testing the spacecraft on the ground produces a set of requirements to be levied on mechanical and electrical ground support equipment that will be instrumental in simulating, stimulating, supporting, and providing the visibility needed for proper verification and validation. One of the most complex of these systems is the avionics electrical ground support equipment. Similar to the flight spacecraft, it also is a VMEbus-based system that uses a distributed computer system for command and control. The design of this electrical ground support equipment is such that custom electronics design was kept to a minimum through the use of easily 'programmable' transition modules and the extensive use of commercial-off-the-shelf equipment. This was a major step in the design of re-usable ground support equipment at JPL, because of the modularity. Nonetheless,

the test setup for a system is itself a system

due to the complexity of the functions and capabilities that needed to be provided. This is an example of the heuristic identified by (Rechtin 1991). The electrical ground support equipment interfaces directly or indirectly to most of the IEM electronic boards on the flight spacecraft and provides either stimulation or simulation. The electrical ground support equipment is used for 'system' integration and test, but can also be used for board-level or stand-alone testing. This eliminates the need for separate bench test equipment, thereby, helping to reduce overall project cost. An example of board level testing is verification and validation of the PCA (Pulse Code Modulation Analog) card. The PCA essential takes analog inputs from temperature transducers and converts this to digital data to be used by the flight processor. The electrical ground support equipment transition module for the PCA provides static, discrete temperature stimulus and this "truth data" information, available through the distributed computer system, is compared with downlinked spacecraft telemetry data. It is with a firm understanding that,

the cost to find and fix a failed part increases by an order of magnitude as that part is successively incorporated into higher levels in the system

Testing at individual component and board levels is considered important and necessary as suggested by (Rechtin's 1991) heuristic above. In the system integration and test configuration, the PCA transition module would provide dynamic stimulus consistent with the spacecraft model's behavior. This leads to a quick introduction and description of the dynamics simulation of the spacecraft. A model of the spacecraft behavior has been developed which provides the appropriate responses to applied forces and torques and also provides appropriate spacecraft sensor data output. This dynamics simulation, another system in itself, has been integrated with the electrical ground support equipment and it being readied for functional and performance testing of the attitude knowledge/estimation and control capabilities that has been delivered to the DS1 Testbed as part of a recent release version of flight software. At times it seems that the electrical ground support equipment and dynamics simulation are actually more complex than the flight spacecraft itself! They have been designed to be compatible with and work in an integrated environment with the flight hardware and software, and therefore, must be as 'smart' or 'smarter' than the capabilities that are being tested. To compound this situation, the requirements definition and design of both the electrical ground support equipment and the dynamics simulation had to be done on a more aggressive schedule, since these capabilities needed to be available, verified, and validated prior to interfacing with flight hardware and software!

Simplify, Simplify, Simplify,

a heuristic identified by (Rechtin 1991) was a definite guideline given the number of challenges presented to the designers and builders of these capabilities, since there was definitely no time to accommodate artificial complexity.

Early on in the development life cycle, an electronic problem report system, accessible through a web browser, was developed and placed in operation even before testing had begun in earnest. This was in recognition of Murphy's Law,

"If anything can go wrong, it will."

a heuristic identified by (Rechtin 1991). It's always hoped that verification and validation will occur without anomalies, but it is a naive individual who believes that the integration and test program will be completed without a number being identified. The electronic problem reporting system helps the project team to,

tally the defects, analyze them, trace them to the source, make corrections, keep a record of what happens afterwards, and keep repeating it,

a heuristic identified by (Rechtin 1991). It's a discipline that's been learned through many years of spacecraft development and is being followed on DS1 for both flight spacecraft integration and test and the DS1 Testbed activities. Problem reports are addressed and disposition once a week, so that a backlog of problems does not hinder the development process. Problems occurring on flight hardware and have the potential of re-occurring in flight are elevated from the problem report to the problem failure report level. Closure of the latter requires significant analysis and verification and the approval of mission assurance. Again, similar to the lab-wide lessons learned file, the problem failure report database is readily accessible to all via the world wide web. This is to better facilitate inter-project communications, and alert those that should know about potential problems with like flight hardware or software.

OTHER MANAGEMENT GUIDELINES

Finally, the project manager developed a small set of guidelines for the entire project team to follow, this to augment the explicit and implicit set of heuristics being used in the design and development of the DS1 spacecraft. These are as follows:

- Select the right people

Select individuals that are technically-capable, team players, responsible, committed and driven to succeed. This is in recognition of the fact that the greatest strengths or assets of the project are the individuals.

- Lead individuals should act as facilitators

Cognizant engineers and management personnel must make every effort to obtain the proper tools and support needed by those doing the technical work. At daily, weekly, and monthly status meetings, identifying areas of needed assistance is one of the most important agenda items. Outside factors that could have an impact into performance, cost, and schedule are identified, discussed, and properly dispositioned. It's interesting to note that on several occasions, resolution only required a telephone call to the correct individual for the hindrance to be eliminated and progress to be resumed. The cost was small, but the benefit was tremendous!

- Use concurrent engineering to solve problems

Concurrent engineering is defined as a 'systematic approach' to the integrated concurrent design of the spacecraft and it's related processes. Project personnel are instructed to utilize the entire team in exploring multiple directions to solve problems.

- Design to cost

Up to the recent past, JPL along with the other NASA centers, were conditioned to believe that if projects or programs experienced budgetary challenges all that was required was to request additional funding from NASA and it would be granted. Performance was arguably the governing factor, and cost and schedule were secondary issues. Today, cost and schedule are as, if not, more important.

- Design and build a capability-driven system

The team was asked not to over-design, and to "accept the acceptable". Rather than strictly building to functional requirements, using what was and is available to accomplish project requirements or goals is adequate.

- Everyone must be a system engineer

The project team was asked to not limit their scope of knowledge and concern to their individual components or subsystems, but to also understand the spacecraft beyond the interfaces. The earlier problems can be identified and resolved, the better the project's position on cost and schedule.

- Empower individuals

The reduction or elimination of non-value added reviews and approvals only helps to expedite project processes. Checks and balances exist where needed, but empowerment conveys a sense of trust and an increased awareness in responsibility for all individuals.

- Instill a "can do" attitude

Encouragement and praise by the management staff conveys a sense of appreciation and a commitment to completing a task or set of tasks in a timely and professional manner.

CONCLUSION

Faced with a complex system to design and develop such as the DS1 spacecraft, the team draws from a wealth of knowledge and insights gained through years of professional experience and lessons learned from other projects and programs, and utilizes heuristic reasoning quite extensively. In most cases, documented heuristics were found to be true and were followed by the project team. In some instances, heuristics were found to be true, but not followed by the project team to one extent or the other due to external forces. These external forces once made to understand the consequences of inflexibility can be used improve the spacecraft development effort and not to hinder it. It was difficult to find examples or arguments to disprove existing and explicit heuristics. Heuristic reasoning provides the DS1 system engineering team with tools that can be used through the completion of design and development, system integration and test program, launch processing and preparations, and finally into mission operations and data analysis.

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BIOGRAPHY

Ralph Basilio is both the DS1 Spacecraft Test Manager and Deputy Avionics Manager. In the past, he has worked on the Mars Pathfinder Project, Cassini Project, Galileo Project, and the United States Space Shuttle Program.